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Doing Without Representations Which Specify What To Do

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Abstract

A discussion is going on in cognitive science about the use of representations to explain how intelligent behavior is generated. In the traditional view, an organism is thought to incorporate representations. These provide an internal model that is used by the organism to instruct the motor apparatus so that the adaptive and anticipatory characteristics of behavior come about. So-called interactionists claim that this representational specification of behavior raises more problems than that it solves. In their view, the notion of internal representational models is to be dispensed with. Instead, behavior is to be explained as the intricate interaction between an embodied organism and the specific make up of an environment. The problem with a non-representational interactive account is that it has severe difficulties with anticipatory, future oriented behavior. The present paper extends the interactionist conceptual framework by drawing on ideas derived from the study of morphogenesis. This extended interactionist framework is based on an analysis of anticipatory behavior as a process which involves multiple spatio-temporal scales of neural, bodily and environmental dynamics. This extended conceptual framework provides the outlines for an explanation of anticipatory behavior without involving a representational specification of future goal states.

1. Representational specification versus organism-environment interaction.

How does the adaptive and anticipatory behavior of humans and animals come about? Cognitive science's usual way of dealing with this problem involves representational specifications: a cognitive system is supposed to incorporate a set of representations which bear an abstract isomorphism to—and so models—the external situation and the system's situation therein. This provides the cognitive system with a model which allows it to anticipate and evaluate the consequences of various behaviors under differing circumstances (Rosen, 1979, 1987). An action can then be selected on the basis of the model's predictions, providing the system with a predefined goal state. After that the model will act as a program instructing the motor apparatus to perform a sequence of movements which will bring about the anticipated goal state. Figure 1 illustrates the basic idea. The box on the left contains the desired state of affairs, the one on the right the state of affairs in the world. Both boxes are described in the same vocabulary, e.g. 'John wants to drink some water' on the left leads to the behavior 'John drinks some water' on the right. In this perspective, behavior is conceptualized as the execution of a pre-programmed set of instructions which will lead to the attainment of a pre-defined goal-state. It is not intrinsically different from translating the stored information on a compact disc into sound waves. Whether these representational specifications are present in symbolical form or e.g. as distributed network states does

not make much difference here. In both cases, a representation of what is to be done is present and used to instruct the motor system. The conceptual framework used remains the same (Keijzer & Bem, 1996).

=== Insert Figure 1 about here ===

Recently an alternative explanation for adaptive behavior has come to the fore. Instead of conceptualizing the outward behavior of humans and animals as the output of an intelligent cognitive system, this alternative explanation stresses the importance of the embodiment of the behaving agent as well as the environment in which the behavior takes place (Beer, 1990; Brooks, 1991a, 1991b; Meyer & Wilson, 1991). This so-called interactionist approach states that behavior is to be explained as a result of the fine-grained interactions between a nervous system, the body it is located in and the environment in which the body is situated. Together these ingredients make up one single encompassing organism-environment interaction system (Beer, 1990; Smithers, 1994), a term that will here be shortened to *behavioral system* (Keijzer & Bem, 1996). The interactionist approach has proven to be quite successful in robotics (Brooks, 1989). It is also closely associated with a more dynamical approach to behavior and cognition (Beer, 1992; Van Gelder, 1992; Thelen & Smith, 1994; Kelso, 1995).¹

The interactionist approach tends to downplay and sometimes even to deny altogether the use of representations as a necessary part of an explanation for the generation of adaptive behavior (Brooks, 1991a; 1991b; Van Gelder, 1992). The notion of representation to which these authors are opposed seems to be relatively specific: an internal modeling capacity which replicates the external environmental structure and which is supposed to be used by the cognitive system to guide its behavior in relative independence from the immediate environment (Keijzer, 1997).

An interactionist account is clearly capable of modelling comparatively simple adaptive behavior without such internal world-models or representations (Meyer & Wilson, 1991; Cliff, Husbands, Meyer & Wilson, 1994). Operational models of behaving systems based on interactionist principles exist and an example will be discussed below. The behavior accounted for by these models remains relatively simple however. The limiting factor seems to be that the environment has to provide enough context for the organism to show appropriate behavior. As long as this is the case, representational specification can be dispensed with.

The real challenge lies with anticipatory behavior. Anticipatory behavior is behavior which involves internal factors which 'lead' or 'guide' the behavior towards attaining specific, future goal-states. Anticipatory behavior, occurring in the here and now, is not only constrained by the immediate environment, but also—in some way—by the to-be-achieved, future state of events. As said, this is the reason for involving representational elements in a behavioral theory in the first place. For the same reason, anticipatory behavior can be considered a so-called representation-hungry problem (Clark, 1997).

Notice that my concern here is only with outwardly observable anticipatory behavior. Anticipatory behavior is often interpreted as involving a subjective sense of anticipating a future result, or intentions to achieve some goal. The present focus is only on behavior. I will maintain a position which is neutral concerning the presence, or lack thereof, of any subjective aspects of anticipatory behavior. There is no denial here of the existence of those subjective aspects, nor of their importance. There is only the claim that topics relating to subjectivity are not the topic which is addressed at present. Anticipatory behavior is strictly interpreted as behavior which is organized on relatively long time-scales while the proximal environment provides insufficient guidance to account for these long-term behavioral patterns.

For the discussion between interactionists and proponents of a more traditional, representation-based explanation, the phenomenon of anticipatory behavior is of prime interest: Could a behavioral theory, based on organism-environment interactions alone, *ever* explain anticipatory behavior? There are good reasons why one would prefer an exclusively interactionist account to one which involves representational specifications. Within cognitive science, representation is a concept with many problems, conceptual as well as practical (Bickhard & Terveen, 1995; Shanon, 1993; Pylyshyn, 1987; Van Gelder, 1992; Brooks, 1991b). Many of those problems would be avoided if behavior could be

explained without invoking representations that specify and instruct the detailed execution of behavior. However, formulating a theory of behavior without resorting to representational specification faces severe difficulties of its own.

In this paper, I will sketch the outlines for an extension of the interactionist account. The key-idea underlying this extension is that interactionism should focus on the fact that behavior is a multiply-scaled phenomenon. Behavior involves patterns at many different scales of organization, ranging from changes within a neuron's ionic potentials, to spatially and temporally extended actions like 'walking to Rome'. Similarly, the interaction between organism and environment occurs at many different spatio-temporal scales. I will argue that explicating the relations between these multiple scales of behavior offers a conceptualization of organism-environment interactions capable of dealing with the future-oriented, anticipatory characteristics of behavior.

If this approach can be made to work, it will offer a theoretical basis for understanding anticipatory behavior without representational specifications instructing the motor apparatus what to do. It will remain a point of discussion whether this does away with the need to talk about representation at all, as is sometimes claimed by interactionists. The account presented does involve features which allow a representational interpretation when seen at a sufficiently large scale. However, the conceptual framework which is presented differs from the traditional one in important ways. It abandons the core idea which the use of a representation-based system embodies in cognitive science: the general notion that behavior is mainly the result of an internal intelligent and knowledgeable system. When this message is accepted, the argument about the continuance of the phrase 'representation' becomes a relatively harmless verbal quibble.

The remainder of this paper is divided into three parts. The next section, relates the interactionist account of adaptive behavior to the topics of spatio-temporal scale and self-organization. Behavior is described as a multiply-scaled, self-organizing phenomenon. The third section extends this picture by drawing an analogy with morphogenesis, the development of a germ cell into a full-grown adult organism. I will argue that the conceptual framework which is now being developed for morphogenesis does provide a theoretical framework along interactionist lines, capable of dealing with anticipatory behavior. The final section will discuss some of the implications of this framework for our understanding of behavior and the role played by representations in behavioral explanation.

2. Adaptive behavior consists of coordinations between differently-scaled dynamics. The interactionist account is based on the idea that behavior is a result of interactions between a neural system, a specific sensory and musculo-skeletal embodiment and the environment in which the embodied system is situated. Detailed accounts can be found elsewhere (Beer, 1990; Meyer & Wilson, 1991; Cliff, Husbands, Meyer & Wilson, 1994). Here I will stress only one major point of the approach: The neural system does not incorporate a complete set of behavioral instructions which are first imposed on the musculo-skeletal system and then on to the environment. Order does not flow from the neural system outward. Instead, the neural system uses the order which is already present in the musculo-skeletal system and the environment. Behavior is subsequently the result of the interactions between the pre-existing order in these systems. It consists of the mutual modulation of neural, bodily and environmental dynamics.

In this section, I will link the interactionist account of behavior explicitly to the topic of scale relations. The coordinations between the neural and musculo-skeletal systems and the environment are to be understood as relations between several differently-scaled dynamics. Neural happenings take place at a smaller scale than movements, which are, in turn, on a smaller scale than the environmental effects that result from them. Scale relations provide a good theoretical basis for understanding adaptive behavior and a starting-point for dealing with anticipatory behavior.

2.1 *The multiple scales of behavioral organization.*

Philip and Phylis Morrison's picturebook 'Powers of Ten' provides a well-known and evocative impression of scale. It consists of a sequence of pictures. The book starts with a picture of the universe at a scale of approximately 1 billion light-years. Each next picture portrays a part of the previous one, magnified by a power of ten. Going from one picture to the next, at first nothing changes very much. You see only white dots on a black ground. Then galaxies appear. Zooming in on our own galaxy, again only white dots are visible until, finally, earth appears. Here we see a few familiar scenes—a view of North-America, Chicago, a picnic on a lakeside, and a hand. As the scale continues to decrease, increasingly more microscopic structure is depicted: a lymphocyte, DNA, atoms and, finally, an impression of quarks. 'Powers of Ten' shows very convincingly that: (a) The scale on which observations are made makes a huge difference for what is conceived of as being there. (b) These scales correspond to multiple levels of organization which are hierarchically configure, ranging from very big to very small. Many scales have their own descriptions and ontology, such as molecules, cells, tissues, planets, or galaxies (Bechtel & Richardson, 1993). (c) Human observers have good differentiating powers at scales with which they are familiar at a day to day basis, but much less so at bigger and smaller scales. What remains outside the book is (d), these effects of changes in scale are typically related to changes in temporal scale (Allen & Starr, 1982). Larger scaled events usually exist on a longer time scale than smaller-scaled events.

The message that 'what is there' actually consists of many different things—depending on how you focus—has often been difficult to digest. The common response is to ask which of the possible descriptions is the 'real' or 'fundamental' one. Heider once said: "The fact of multiple focus furnishes philosophy with many of its classical problems. Multiple focus is distasteful to thinking ... It is as if it were possible to read the same book in two ways; once by organizing the letter configurations into English sentences, and then again by organizing them into German sentences." (Heider, 1959, p.64). This distaste also shows in the strong appeal of physical reductionism. According to this view there are no real levels. Each level is no more than the sum of its parts, and ultimately a single dynamics should suffice to describe everything. Strictly, this would amount to the claim that nothing 'really' happens except for the most basic physical happenings, quantum events. This is a very high price to pay for a non-ambiguous way of carving up the world. Nowadays, for all practical and scientific purposes it is generally accepted that the world clusters into multiple levels of organization, without each level being a linear derivative of the preceding level (Anderson, 1972; Bechtel & Richardson, 1993; Weiss, 1971; Yates, 1993). This means that there is a scalar hierarchy of natural phenomena in which it does not make much sense to ask which one is more 'real' or fundamental than the other (Bechtel, 1994).

It is one thing to acknowledge that the world is organized along multiple levels. It is quite another thing to address the implications of this general organization. Dividing the world in levels is an accepted and necessary way to divide scientific labor. It allows scientists to investigate isolated, specialized topics. However, as will be discussed below, a multiply-scaled organization is itself a topic worth of serious research. This latter aspect of the multi-level world has only fairly recently been turned to. It offers a number of interesting explanatory notions that can be used for behavior.

An analysis in terms of multiple scales of organization applies well to behavioral phenomena. Behavior involves processes that extend over a wide range of spatio-temporal scales, ranging from molecular and cellular happenings within the nervous system, to muscle contractions, to relatively small-scaled simple behavior, and on to actions which consist of increasingly large spatio-temporal patterns, such as the yearly migration of knots which breed on the arctic tundra and spend the rest of the season in coastal intertidal areas on the other side of the earth. The interpretation of this kind of migrating bird's behavior at any particular time is scale-dependant. The knot's behavior can be described as flapping its wings, flying, flying north, or flying towards Lapland. The multiplicity of behavioral interpretations is even greater for humans. Take, for example, a person sitting in front of a computer, typing. What is he doing?

Is he alternatively tensing and relaxing muscles in his arms? Yes. Is he moving his fingers up and down? Yes. Is he typing strings of symbols? Yes. Is he adding a return instruction that he forgot at the end of a subroutine? Yes. Is he writing a program for plotting stock

market prices? Yes. Is he making a little extra money for a vacation? Yes. Is he justifying his hobby to his family? Yes. (Powers, 1979, p.134)

Each of these descriptions forms an equally acceptable description of the 'same' behavior. The same typing movements can be related to diverging sets of environmental happenings. Selling a computer program involves a different set of consequent environmental happenings compared to those of the vacation which is paid for by the program. These environmental happenings can also vary a great deal in the time and space that they involve. For example, moving a finger takes much less time and space than justifying a hobby to your family, which involves first making money and subsequently spending it on a vacation-trip.

Behavior thus involves many different scales. Yet, conceptually, its organization across those multiple spatio-temporal scales is not a well-explored territory. One reason is probably the general aversion of multiply scaled explanations, mentioned above. A more specific reason comes from the practice of using the intentional vocabulary to describe what agents do. Describing the agent and his behavior in an intentional language obscures the scale relations involved. The intentional idiom relies on a symbolical description of the agent's intentions. Being symbolical, the question of relating small processes to large processes does not arise. Intentions have no size. Nor is the size of a symbolical expression in any way related to the size of the entity referred to. The word 'universe' takes as much space as the word 'molecule'. An intentional description of behavior can thus feature events of any size in its behavioral program. The result is the image given by Figure 1. The contents of both boxes can be described in the same terms. The fact that representational specifications, as neurally instantiated entities, are much smaller than the outward behavior for which they thought to form the program remains unaddressed and is even taken to be beside the point.

In this paper I will further ignore the intentional interpretation of behavior. Behavior will be interpreted as a complex spatio-temporal set of happenings. There will be made no reference to an agent who instigates and instructs the behavior. To mark this I will talk about organisms, both for its more neutral connotations and to stress the biological background of behavioral phenomena. This is not a reductive step. I *ignore* agency here. I do not deny it. At a suitably high level of organization the concept seems to apply very well (Bechtel, 1994; Keijzer & Bem, 1996). But the present enterprise is concerned with a different topic, namely the levels of organization which bring agent-related phenomena into being. To put it more down to earth; To understand how a car works, you will have to figure out how a collection of car-parts is assembled so that together they come to exhibit a totally new property: automotive power. You cannot deal with this problem by assuming that this 'automotive power' somehow has to reside within the parts. I hold that the same goes for agency.

Without the intentional interpretation of the organism, the topic of relating processes at many different spatio-temporal scales comes to the fore immediately. The biological context of behavior provides ample evidence of the importance of spatio-temporal scale. Growing bigger is one of the major evolutionary trends and is closely associated with increased complexity (Bonner, 1988, 1993). Living organizations started out as complex, autocatalytic sets of biochemical processes (Maynard-Smith & Szatmáry, 1995), which gave rise to cellular life at least 3.5 billion years ago (Gould, 1994). The fundamental interactions between a living organization and its environment thus occur at the molecular and cellular scales. Only much later, about 530 years ago, the famous Cambrian explosion took place. In a mere 5 million years all but one modern phylum of animal life made their first appearance in the fossil record (ibid.). These multi-cellular organisms extended the range of organism-environment interactions to the much larger spatio-temporal scales with which we are familiar from everyday life—roughly the range between millimeters and kilometers.

The new scales of interaction opened up a whole new range of potential interactions (Breland & Breland, 1966; Maturana & Varela, 1988). A multicellular organization is not a simple magnification of an unicellular organism, which would look like an amorphous blob of living tissue. Instead, new, large-scale structures are generated to exploit the possibilities of this new, large-scale level for the benefit of the cellular basis of life. The structure of plants is one example. Plants grow stalks which lift light-catching leafs above potential obstructions and they grow roots which reach underground reservoirs of

water. Plant structure exploits the large-scale environmental characteristics in which light comes from above while water can be found underground).

Additionally, a living organization can come to interact with its environment at the scale of its multi-cellular body by self-initiated, reversible movement, without addition in tissue. Reversible movement offers a way to manipulate large-scaled environmental events, otherwise left to chance alone, in a way which is less costly and *much* faster than growth. Here, adaptive behavior has its origins. Compared to the plant strategy of building 'permanent' structures, the ingenuity of even the most simple of behaviors is remarkable. When environmental circumstances become less agreeable, an organism does not have to stick it out or die. It can move away, or even change the disagreeable circumstances into something more congenial. By means of reversible movement, an organism can influence environmental happenings at scales far larger than its own body: Food is sought and found over wide areas and subsequently ingested, the body's integrity is maintained by avoiding harmful situations and so on. The capacity for behavior—which is the result of these reversible movements—is an extraordinary feat for what is initially a multi-cellular sack of goo.

Motor capacities and a nervous system play the key roles in extending the scale of interaction. Specialized cells capable of contracting make it possible for the multi-cellular organism to move as a whole. A nervous system made up from a network of cells which activate one another and the motor cells allows for the fast coordination of the capacity for self-initiated movement across the scale of the whole body. The capacity for coordinated motion at the bodily scale can, in turn, be modulated by specific sensory cues, and ultimately by very sophisticated sensory processes, which make possible the coordinated manipulation of the large-scale environment. Neural, bodily and large-scale environmental dynamics become linked to one another. Behavior, interpreted as a subpersonal process, thus involves a spatio-temporal structure extending over multiple scales of organization. Somehow, the large-scale dynamics have to be harnessed to benefit the small-scale dynamics of the living organization. A way to come to grips with these properties is by turning to the theory of self-organizing systems.

2.2 Self-organization: Dynamical relations between scalar levels.

The idea of multiple levels of organization implies that a distinction has to be made between happenings within one scalar level and relations between different scalar levels of organization. A simple metaphor can be enlightening here. The traditional image of basic happenings is that of simple elements, endlessly moving and colliding with one another. Once the position, direction and force of each element is exactly known, dynamical laws allow the exact prediction of all future and—because of the time symmetry here—past states of the system. The elements within such a system can be said to traverse an exactly specifiable 'Newtonian trajectory' (Yates, 1993). The description of simple colliding elements can be applied to different levels of organization. Depending on the focus used, the described trajectory could be either that of a molecule in a gas or of a billiard-ball on a pool-table. This raises the question of how to describe the relation between the molecules—which make up the billiard-ball—and the billiard-ball as a whole. The Newtonian picture does not deal with the relations between different ontologies. Molecules do not collide with billiard-balls, they collide with other molecules, those which make up the billiard-ball. In principle, the Newtonian view treats the larger-scaled phenomenon in a reductive way. The billiard-ball is just a large collection of molecules. In practice, this view treats the separate dynamics independently from one another. In both cases, relations *between* differently-scaled dynamics are left out of the picture.

Accepting the multiple scales of natural organization as a fact, how should the dynamical relations between those scales be described? A standard answer here is that there are (almost) no such dynamical relations. Different scalar levels arise and can be treated as independent systems because the interactions with different levels are severely restricted (Simon, 1973; Salthe, 1985). If there were close dynamical interactions, the processes making up the different levels would not be dissociated from one another. With a change of scale the average rate with which processes take place changes as well. These rate differences restrict dynamical interactions between differently scaled events. For example, the dynamics within a single molecule are so fast compared to the dynamics of the billiard ball that the latter does not change at all within the molecular time frame. Given a focal scale $S(n)$, dynamical changes at a

scale $S(n+1)$ are so slow that, compared to processes happening at $S(n)$, they do not change at all. Changes at $S(n-1)$ on the other hand are so fast that they do not occur as individual events at $S(n)$. Happenings at $S(n-1)$ have to be averaged to describe their influence on $S(n)$. As a result, both figure as (different) constants in the equations describing focal level dynamics (Salthe, 1985). The isolated dynamics cluster into separate levels which together make up a scalar hierarchy.

Nevertheless, while scalar levels may be independent of one another in general, there are many exceptions to this rule. In particular when living systems are concerned, processes happening at different scales can be closely connected. There is also a straightforward explanation for such coordinations between differently scaled dynamics. Given a clustering into separate levels as a consequence of rate differences, manipulating the rate changes at a specific scale would enable dynamical interactions between differently scaled dynamics. The different scales would no longer be independent under such circumstances. This type of speeding up and slowing down definitely occurs. The rate at which chemical reactions take place, for instance, is not only sensitive to the large scale boundary conditions (temperature) but also to the presence of catalysts which operate within the same scalar level. The rate of change is thus variable at a specific scale, and different scales can dynamically interact.

The study of self-organizing systems addresses the relations between differently-scaled, so-called microscopic and macroscopic, events. As pointed out above, in the original Newtonian view on dynamics there were no different levels. The development of thermodynamics in the nineteenth century changed the picture in so far that it now made sense to talk about the collective properties of many parts in terms of simple, large scaled variables like heat and pressure. However, the second law of thermodynamics, then formulated, states that natural systems tend towards a state of thermal equilibrium where disorder is maximal. There did not seem to be many possibilities for the generation of large scale *order* as a collective property of many interacting parts. Only fairly recently has it been established that under specific circumstances—in systems pumped with energy and thus far from thermal equilibrium—large scale order does result from the interactions of small scaled parts (Prigogine & Stengers, 1984; Gleick, 1987; Haken, 1987). One of the impressive early examples which helped to bring this message home consists of a chemical reaction discovered by Belousov and Zhabotinskii in the fifties. Some chemicals diffusing in a solution in a shallow glass dish produce concentric circles and spiral waves across the solution's surface (Goodwin, 1994). Since then, the occurrence of large-scale, or macroscopic, patterns from small-scale, or microscopic, interactions have become a widely established phenomenon.

I will introduce two concepts which have been developed in the study of self-organizing systems—the order parameter and the control parameter (Haken, 1987)—by looking at a system of coupled oscillators (Strogatz & Stewart, 1993; Matthews & Strogatz, 1990; Stewart & Golubitsky, 1992). An oscillator is any system which executes periodic behavior, for example a clock, a flashing firefly, a neural rhythm or a dripping faucet. When an oscillator has a stable—that is perturbation resistant—frequency and amplitude it is called a limit-cycle oscillator. A limit-cycle oscillator has a dissipative mechanism to damp oscillations that grow too large and a source of energy to pump up those that become too small. The paradigmatic example is the pendulum clock. Such clocks also illustrate the coupling or entrainment of oscillators. Christiaan Huygens discovered in 1665 that two pendulum clocks hanging on a common support tend to synchronize (Strogatz & Stewart, 1993). When hung more widely apart, the clocks lose this perfect synchrony. This mutual influence of two separate oscillators is called *coupling*. In this case only two oscillators were present, but it is also possible to have a large group of coupled oscillators, such as a swarm of fireflies or a collection of neural elements which show individual oscillatory activity. In a large system of coupled oscillators interesting things can happen. Because of the mutual influence of the individual oscillators, global synchronization can occur at a much larger temporal scale than the cycles of the individual oscillators. The system as a whole can show large scale order, even when the individual oscillators diverge in their amplitude and their individual frequency. The large-scale order of the system can then be described by a simple *order parameter* or *collective variable* (Haken, 1987; Kelso, 1995).

Haken first developed his order parameter concept when working on the laser. This concept is based on a so-called linear stability analysis: An initial random starting pattern can be described as the superposition of many different vibratory modes. A system of coupled oscillators slightly out of phase

and frequency would be an example. Given random initial conditions, some, or even most, of these different modes will be damped out. At the same time, others will expand across the system. The mode or pattern with the biggest rate of increase will eventually dominate the total system. The order parameter describes the resulting, large-scale coherent pattern which exhibits its own large-scale characteristics. Haken describes the mutual influence between the macroscopic order parameter and the microscopic oscillations as *circular causality* (Kelso, 1995; Haken, 1995). The large-scale order parameter acts as an independent entity which constrains—Haken says enslaves—the activity of the small-scale individual oscillators. At the same time, the small-scale individual oscillators together generate a large-scale order parameter. The influence is mutual, neither is primary to the other one.

The second important concept is that of a *control parameter*. This is usually an experimentally manipulatable parameter to which the collective behavior of the system is sensitive. When a control parameter is changed, the system of coupled oscillators may start to exhibit different order parameters. In this case, the system undergoes a so-called phase shift. So far, for reasons of mathematical tractability, primarily systems in which each oscillator is coupled equally to each of the others have been investigated (Matthews & Strogatz, 1990). Under these circumstances, changing the coupling strength by which each oscillator influences the other ones or the spread of the individual oscillator frequencies results in typical macroscopic behaviors, for example locking, incoherence and amplitude death (ibid.). In these cases, the density of interaction can thus be used as a control parameter to modulate large-scale phase shifts of the macroscopic order parameter.

The word 'control parameter' is a bit unfortunate, as it invokes associations with control theory and a controller. However, the control parameter does not 'control' the system in any conventional sense. The order comes from the system itself. The control parameter does not prescribe what the system should do. This parameter is an externally modifiable variable that pushes the system into different forms of self-organized order. It is a mere non-specific trigger with respect to the changed dynamics of the self-organizing system. The non-specific control parameter concept is a very powerful challenge to the accepted machine and computer metaphors of biological order (Thelen & Smith, 1994, p.62), and will play a prominent role when discussing anticipatory behavior.

2.3 Coordinations between neural, bodily and environmental dynamics.

The self-organization of systems of coupled oscillators offers a new way to understand the operation of a nervous system (Alexander & Globus, 1996; Bickhard & Terveen, 1995; see also Kortmulder & Feuth-de Bruijn, 1993). In behavioral explanations based on representational specification the activity of neurons is interpreted as an input-output device which receives and sends information. However, neurons can also easily be interpreted as oscillatory units (Alexander & Globus, 1996). Given this interpretation, the total nervous system forms a larger oscillatory network, the behavior of which depends on the characteristics of its components and their connections. As the nervous system is an organ that extends itself over the scale of the total body of an organism, and because the connections between neurons allow very swift interactions across this network, it forms a means for dynamical patterns to organize themselves very fast (starting at tens of milliseconds) at the bodily scale. In turn, the neural dynamics is tied to a musculo-skeletal system capable of initiating environmental changes at the bodily scale. The bodily dynamics in turn influences dynamical relations within the environment.

This multiply-scaled conceptualization of adaptive behavior is a good way to describe the behavioral systems approach to behavior. The most famous early example of this approach consists probably of Rodney Brooks' behavior based robots (Brooks, 1989). A local operating control structure helps to organize the dynamics of a robot's moving parts. The robot so becomes capable of standing up, moving forward and achieve a number of other tasks in the environment. Work done by Taga on bipedal locomotion provides an example which is explicitly formulated as the coordination of several differently-scaled dynamics (Taga, 1994; Taga, Yamaguchi & Shimizu, 1991). The model consists of a rhythm generating neural network, a musculo-skeletal system and an environment (Figure 2a). These act in parallel as three dynamical systems which mutually entrain one another and therefore become and remain coordinated. The total result is bipedal locomotion which remains stable when perturbed. The

neural rhythm generator generates spatio-temporal patterns of activity without any external input. These patterns provide the motor signals which set the musculo-skeletal system into motion. The latter consists of two legs, each composed of a hip-, knee- and ankle joint and a thigh and shank (Figure 2b). The legs are connected together at the hip joint. The musculo-skeletal system moves according to its own dynamics, given the constraints of the environment and the motor signals. It can be thought of as a swing which has its own momentum while it is kept in motion by someone who pushes it at the right moments. Sensory signals which indicate the current state of the musculo-skeletal system and the environment are sent to the neural rhythm generator. These signals in turn entrain the centrally generated neural rhythm and allow it to adapt to the limbs' actual rhythm. The total neuro-musculo-skeletal system is situated on a stable limit cycle in the system's state space. Unpredictable environmental influences on the system, for instance changes in the profile of the ground which disturb the limbs' rhythm, are neutralized by the orbital stability of the limit cycle. Changes in the gait patterns are produced by bifurcations of the limit cycle. The whole system in turn is influenced by a central control parameter which changes the level of activity of the neural rhythm generator. Changes in this parameter induce changes in speed as well as changes in the gait between walking and running.

=== insert Figure 2 about here ===

Similar models of the mutually flexible entraining between neural rhythm generators and the rhythm of the musculo-skeletal are also employed in neuroethology. Camhi, for example, describes how locust flight involves the coaction of oscillators at two different scales. A neural oscillator tends to impose a steady rhythm on the wings, while the wing's actual oscillations are used to modulate the neural oscillator so that the locust can react flexibly to differing environmental circumstances (Camhi, 1984, p.353). A similar interaction between neural and bodily oscillations has been established for leech swimming (Cohen, Rossignol & Grillner, 1988).

A scalar interpretation in which several dynamical levels of organization are coupled and generate the spatio-temporal patterns of behavior in a self-organizing process agrees very well with actual models of adaptive behavior in artificial and real agents. The behavior which such models can generate remains limited, however: It consists of short-term repeatable behavior which is well adapted to the local, so-called *proximal*, environment. Adaptive longer-term behavioral sequences are not accounted for.

It is self-evident that, given time, the continuous locomotion generated by a model such as that of Taga will allow a behaving system to travel large distances. However, for biological organisms long-distance movement is usually oriented towards specific places, objects or events which have to be reached or achieved. Such a large scale, or *distal* orientation of behavior is often maintained despite many intervening environmental disturbances. Taga's model, for example, has no such capacity. It can only counteract environmental disturbances on the walking movement itself. A mere walking mechanism will only walk forward, and not towards a goal. If someone pointed it in the right direction at the beginning, any disturbance would throw it off course.

The obvious solution is to use sensory signals to steer the behavior. This would allow a behaving system to orient itself with respect to its environment at a relatively large scale and to maintain a stable distal course. For example, a behaving system might steer towards a directed source of sensory stimulation by maintaining an even input at two frontally placed sensors (Loeb, 1918; Braitenberg, 1984). In this way the distal goal can be reached despite disturbances. This solution remains very limited, however, as it depends on unambiguous local signals which reliably specify distal circumstances (Campbell, 1966; Fodor, 1986). For many behaviors there are no such local stimuli. For example, the lion goes in search of a prey, it does not wait till it sees, smells or hears one. Proximal guidance will never be the full story.

Here we enter the next stage in the discussion on representation. Those in favor of a representation-based explanation of behavior hold that, for an organism to exhibit behavior which is oriented towards the non-local environment, it will be necessary for the organism to have an internal representational model to act as the relevant guiding factor (Clark, 1997; Clark & Toribio, 1994;

Jeannerod, 1997; Rosen, 1987). I do agree that pure interactionism faces severe problems here. On the other hand, I do also think that the problems connected to representation-based accounts are even worse (Keijzer, 1997). While acknowledging the problems faced by interactionism, one should still try to extend the interactionist approach so that it does become capable of coping with anticipatory behavior. This is what I will do in the next section.

3. Applying a morphogenetic conceptual framework to anticipatory behavior.

Adaptive behavior has been interpreted as a macroscopic structure that emerges from the self-organizing interplay between micro- and macroscopic processes. To deal with specific *anticipatory* behavior it will be necessary to extend our thinking in terms of micro-macro interactions. An interactionist conceptual framework is required which is able to deal with distal goal-orientedness. More specifically, the conceptual framework should explain how specific long-term spatio-temporal structure arises (distally oriented behavior) of which the short-term constituents can be interpreted as arising 'in order to' achieve the distal goal.

The new territory for thinking in terms of micro-macro interactions consists of the multiple scales of behavior itself. The relations between smaller- (e.g. movements) and larger-scaled behavior (e.g. functional goal achievements) are to be interpreted as a coordination between micro- and macroscopic events.

3.1 Similarities between morphogenesis and behavior.

The first step towards an extended interactionist conceptual framework consists of drawing an analogy between anticipatory behavior and morphogenesis. Morphogenesis is the process by which a single germ cell grows into a highly complex and differentiated multicellular organization. How this comes about has been a long-standing problem in biology and forms the topic of embryology or, to mention the more modern expression, developmental biology. How, for example, after a number of cell-divisions, does a cell 'know' that it has to turn into epidermis while its neighbor becomes part of the nervous system? Important constitutive principles at a microscopic scale, like cell movements, cell death and cell differentiation (Edelman, 1988), all happen in real time in order to generate a particular multicellular structure on a larger time scale. The process of morphogenesis leads consistently and (particularly for big and complex organisms) in non-stereotypical ways to a highly specific goal state: a multicellular body with the right parts in the right place. As in the case of behavior, disturbances of the normal course of events can be counteracted up to a point. If they are not, specific deformations occur.

There are several reasons why someone interested in behavior might take a closer look at morphogenesis. For one, the structure of a nervous system is itself a result of morphogenetic processes. These processes are thus directly relevant for the construction of one of the most important factors in behavioral organization. Foremost, however, I want to stress the conceptual similarity of morphogenesis and behavior which was, for example, already noted by Lashley (1951; see also Kelso, 1995). Both processes can be described as goal oriented, regularly resulting in a well-formed adult body and an achieved act respectively. In both cases, this anticipatory character tends to be explained by representational specifications, localized either in the genes or in the brain (Pattee, 1977, 1987).

An important difference between morphogenesis and behavior consists of the detailed knowledge of the processes involved in morphogenesis. In the case of morphogenesis, both the material substrates of the microscopic 'symbolical description' and the macroscopic form are known. Genes, encoded in DNA, provide a concrete embodiment of the 'symbolical description', while it is not established which feature of a nervous system would be its behavioral equivalent. The same goes for the large-scale, behavioral equivalent of bodily form. Behavior is in large part a temporal structure, consisting of patterns in time (Eibl-Eibesfeld, 1970). It is not naturally fixated in matter, such as body tissues. Behavior's fleeting structure requires recording techniques such as video or abstract notations to fixate the temporal pattern in a spatial form that can be studied at leisure (Berridge, 1990; Fentress, 1994; Jacobs, *et al.* 1988). The systematic and particularly the detailed study of behavioral form has

consequently had a late start compared to the study of bodily form. Even now there is no generally accepted way of encoding behavioral structure and a lot of work is still based on highly intuitive notions (Jacobs, *et al.* 1988). Embryology is thus a field which addresses a problem very similar to behavior, but with much more background knowledge of the concrete details involved. Its way of conceptualizing and modeling the relation between 'symbolical descriptions' and macroscopic form is highly corroborated by a relatively detailed knowledge of the actual processes happening in between. An account of behavior could benefit greatly from the ideas and models developed here.

Both morphogenesis and behavior have given rise to the idea of representational specifications. How this is thought to work for behavior has been discussed above, but the case of morphogenesis deserves attention here. The idea that a genetic program specifies body form implies a separation of the genetic information and the process by which this information is turned into a multicellular organism. This separation is reflected in the distinction between the biological fields of genetics and embryology. Embryology is mainly concerned with the developmental process within the individual. The embryologist's question is "How does a germ cell develop into a multicellular organism?" In the nineteenth century and in the first half of the twentieth century, the study of morphogenesis turned from a mainly descriptive into a real experimental science. Many details of the developmental process, as well as ways to manipulate it experimentally, were discovered, for instance by grafting cells taken from one place on another part of the embryo, adding chemicals and so on (Gilbert, 1991; Gottlieb, 1992). The embryologist's focus was thus on the intricacies of the developmental processes which happen within the cellular cytoplasm and on the interactions between cells.

However, starting in the 1920s, embryology as a front line science was largely overtaken by developments within the new and vigorous field of genetics. In the 1930s, Mendelian genetics and Darwin's model of variation and selection were welded together to form the 'modern synthesis' or 'neodarwinism' (Depew & Weber, 1995; Gottlieb, 1992). The modern synthesis brought biology what it did not have before—a coherent theoretical basis: Life on earth was the result of genetic variation and consequent selection. In contrast to embryology's interest in the cytoplasmic processes leading up to a grown individual organism, the new view stressed the importance of the genetic program to a very high degree. Interest became much more explicitly and exclusively focussed on the contingency of evolutionary processes, in contrast to the search for general principles underlying individual development (Resnik, 1994; Gottlieb, 1992). Genes were the entities that could vary and were transmitted from one generation to the next. These were the entities that mattered for evolution theory and it was thought that gene action alone could explain everything that a biologist might be interested in. The embryological questions became viewed as less relevant than questions relating to shifts in gene frequencies: "the great bulk ... of the protoplasm [is], after all, only a by-product of the action of the gene material" (Muller, 1926, quoted in Keller, 1995, p.8). American geneticists in the twenties started to talk about gene action as if it was self-evident what that meant. The embryologist's question "How does a germ cell develop into a multicellular organism?" was replaced by another: "How do genes produce their effects?" What happened in between was not conceived of as an interesting topic in its own right but was seen as a "chain of reactions" leading from the gene to the gene's effect.

This was the context in which genes could be interpreted as the 'brain' of a cell (Keller, 1995). The cell's nucleus (and in particular its DNA) became the initiator of intelligent action which instructed the cell's cytoplasm to do what was necessary to achieve the cell's goals. As far as the genesis of multicellular structure is concerned, these ideas led to a conceptual schema in which genes are the symbolical encodings of large scale traits, to which they are connected by a causal chain. This can be envisioned in the same way as the relation between representational specifications and the resulting behavior (see Figure 1). The conceptual overlap between anticipatory behavior and morphogenesis should be clear by now. But what relevance does it have for an interactionist account of behavior? So far, morphogenesis is just another explanation in terms of representational specifications.

3.2 *Genes do not specify traits, they act in mutual interaction with the cytoplasm.*

The geneticists ignored the cytoplasmic complexities of morphogenesis and searched instead for simple relations between genes and traits. This approach turned out to be extremely productive. In 1940 Beadle

and Tatum proposed an explanation of how genes produce their effects in a form that came to be known as the 'one gene-one enzyme' hypothesis (Keller, 1995, p.17). The most important success was, of course, Crick and Watson's discovery of the structure of DNA as the molecular basis of genes in 1953. The long and variable sequences of base pairs making up the DNA molecules gave material evidence of entities which were previously theoretical. DNA sequences explained how the reproduction of genetic traits takes place across generations. They also offered a 'code-book' for prescribing the composition of proteins which could act as enzymes. Gene action could now be understood as DNA coding for specific enzymes. These basic insights led to the subsequent rise of molecular biology and an explosion of insight into the details of molecular interactions within and between cells.

Ironically, as a result of the increasingly detailed knowledge of the molecular operation of genes, somehow the experimental frame of reference changed. It became more and more clear that genes were not the sole, or even the major, locus of control. They did not, in a uni-directional way, instigate protein building and subsequently macroscopic structure. Instead, the genetic code is part of an intricate, parallel and reciprocal interaction with cytoplasmic processes, which are at least as much in control as the genetic material (Nijhout, 1990). Talk about 'gene action' was replaced by 'gene activation' (Keller, 1995, p.26). DNA is not directly transcribed into proteins, but first into nuclear RNA (in multicellular organisms at least), then into messenger RNA, and only then into proteins. All these steps are modulated by cytoplasmic processes and can even lead to one gene coding for more than one protein (Kauffman, 1993, p.416). Another thing that has become clear is that many genes do not code for proteins at all. These genes are not 'structural genes' but 'regulatory' ones. Regulatory genes influence the transcription of structural genes in direct or indirect ways. For example, *promoters* are DNA sites situated near a structural gene. When the promoter is bound by (reacts with) a specific molecular 'key' transcription takes place. Unless, of course, an *operator* site, situated between the promoter and the structural site, blocks transcription. This happens when the operator is bound by the presence of its own molecular key. In turn, the operator's block can be removed again by the presence of yet another molecular key. Kauffman calls this organization a "genetic regulatory network" (Kauffman, 1993, p.417). This is not a static array but a dynamical organization "made up of all the complex feedback webs and cycles of control acting at all these levels" (ibid.). Again, this network is not only genetic. Cytoplasmic factors are important in initiating and maintaining proper regulation. The mutually influencing genetic, cytoplasmic and larger-scaled factors make up a very complex regulative network, in which no single entity forms *the* locus of control. This is a large step away from the initial thought that genes direct the cytoplasm and so determine bodily form.

The drift away from the idea of any direct gene action becomes even greater when considering the relation between genes which do code for proteins and larger scaled processes, such as cell differentiation and tissue formation. Gene products change the direction in which specific cells or tissues develop, but not by directly specifying the proper end result. Instead, the embryological frame of reference has again come to the fore: Gene products tend to direct the developing organism into specific epigenetic pathways. An epigenetic pathway (Waddington, 1975) can be visualized as floating downstream into a river delta. An undifferentiated germ cell starts at the undivided point and subsequently choices have to be made between successive right and left turns. The consecutive choices decide which branch of the river—or, correspondingly, which multicellular structure—is reached. Gene products can initiate choices, whether to go 'right' or 'left', at particular turns within this epigenetic landscape. On the other hand, genes do not direct the layout of the epigenetic landscape. Their activity depends on and is limited by the features of the landscape which it confronts. The landscape itself is a cumulative result of all the variables which influence morphogenesis on all relevant scales. The developing embryo is an unstable dynamical system which has many time- and space-dependent dispositions for further development. Gene products can trigger such propensities, but so can many other non-specific 'signals' in an experimental setup when the system is situated at a branching point.

A concrete example will make more clear what genes do and what they do not do. Take the process of neurulation, the beginning of the formation of the nervous system in vertebrates. After a previous developmental stage called gastrulation, the embryo consists of three basic germ layers; the most inward is called the endoderm, the middle is the mesoderm, and the most outward is the ectoderm.

The endoderm is destined to become the gut and related structures. The mesoderm turns into skeleton, connective tissues and muscles. The ectoderm becomes epidermis and the nervous system. At some point in development, the ectoderm must thus differentiate into the nervous system on the one hand, and epidermis on the other. This happens when on the dorsal side—the embryo's 'back'—the part of the ectoderm layer which will become nervous system folds inward to form an elongated groove. This inward folding of ectodermal cells continues until a separated, closed neural tube is formed. This tube is situated underneath the remaining ectoderm which closes above it and develops further into epidermis (Gilbert, 1994). The neural tube differentiates further to form the nervous system. The process of neurulation is triggered by chemical "inducing factors" originating in the underlying mesoderm. The exact relation of these inducing factors to the genetic regulatory network is unclear in vertebrates (which show neurulation). "Knowledge of the cellular mechanisms of pattern formation is more extensive in studies of vertebrate species, whereas knowledge of the genetic control of pattern is most developed in studies of invertebrates." (Edelman, 1988, p.26; see also Slack, 1991). It is, however, plausible that a genetic regulatory network comparable to that of invertebrates instigates the release of the proper inducing factor. What is surprising here is that the inducing factor is very unspecific, no more than a trigger which initiates the process of neurulation. Once set in motion, the rather complex set of happenings runs its own course. This was already discovered in the 1930s when it was shown that ectoderm could be turned into neural tissue by introducing many different and nonspecific factors into a cell culture, such as alcohol and even distilled water (Holtfreter, 1991, p.121). Thus "it became clear that the ectoderm was delicately balanced between epidermal and neural pathways and that a variety of stimuli could tip the balance one way or the other." (Slack, 1991, p.106). The increased insight into molecular biology allows the revindication of these old findings in the context of genetic functioning.

Kauffman summarizes the case as follows: "Morphogenesis is not just the genome's 'doing'; rather, it is the consequence in time and space of the structural and catalytic properties of proteins encoded in time and space by the genome, acting in concert with nonprotein materials and with physical and chemical forces to yield reliable forms." (1993, p.410). Genes do not instruct the cytoplasm, they rely on the intrinsic disposition of cytoplasmic processes to generate spatial and temporal structure. As Gottlieb puts it, genes are a part of a complex but highly coordinated system of regulatory dynamics that operate simultaneously at multiple scales, extending from genes to chromosomes, to the cell's nucleus, cytoplasm, tissues and up to the whole organism (Gottlieb, 1992, p.142).

3.3 A dynamical interpretation: Genes act as internal control parameters.

Molecular biology is primarily concerned with unravelling the specific details of the molecular interactions within living organisms. A more theoretical approach is now proposed by e.g. Stuart Kauffman (1993) and Brian Goodwin (1994; Goodwin, Kauffman & Murray, 1993; Boyd & Noble, 1993). Kauffman and Goodwin try to give a more general, and a more abstracted, understanding of the minute molecular interactions. They search for general principles characterizing these interactions. They stress the self-organizing properties of the living organization. Many small-scale interactions in the living organization give rise to order at a larger scale and these, in turn, on still larger scales. The topic of self-organization has already been discussed above. The new thing here is the implication of the genome.² When genes are no longer to be seen as specifying what the cell has to do, then what do genes do? Goodwin and Kauffman argue that the order exhibited by living organisms is largely the result of inherent, dynamical ordering principles which are a general feature of all of nature. In this respect they hark back to the rational morphologists of the nineteenth century who sought general organizing principles in living nature and eschewed the selectionist ideas of Darwin because these would make living systems a hodgepodge of independent traits which could either be present or not (Resnik, 1994).

The general picture sketched by people like Kauffman and Goodwin is as follows. Self-organizing systems produce macroscopic order. This order is not the result from genetic instructions, but results from the intrinsic dispositions of dynamical, non-equilibrium systems. Such systems conform to a macroscopic order parameter when certain boundary conditions are met. This order is highly specific and arises predictably when, and as long as, the proper control parameters are present. When the control

parameters change, a different order parameter can occur or order can disappear. Ordinarily, the presence of control parameters is a matter of chance. Either there is a heat gradient or an enzyme present, or not. However, if things are not left to chance, then the manipulation of control parameters offers a means to influence the order parameter in predictable ways. If a self-organizing system were to be exposed to specific sets, sequences and distributions of control parameters, this could lead to a highly specific and intricate macroscopic structure which would never occur when left to chance (Pattee, 1987). The whole process would be even more geared to generate specific macroscopic order when the control parameters could be turned on and off by the same self-organizing process in an appropriate way. Kauffman's genetic regulatory network offers a way in which this switching could take place.

It is easy to see how the gene-cytoplasm relations could be interpreted as such a self-modulating, self-organizing system. The cytoplasm exhibits self-organizing properties which, under the influence of specific gene products, could be guided over longer time scales to develop an appropriate multicellular structure (Goodwin, 1994, p.97; see also Kelso, 1995, p.140). Genes can then be interpreted as control parameters which are internal to the system, *Internal Control Parameters* (ICP) for short (Meijer & Bongaardt, 1996). This interpretation offers a more general, theoretical understanding of the role played by genes in the self-organizing cytoplasmic processes resulting in the formation of specific macroscopic structures. Of course, it is an idealization which glosses over all the actual molecular, cellular and intercellular intricacies involved (Slack, 1991; Edelman, 1988). On the other hand, it is just the sort of idealization which is needed: It gives a general conceptual framework which allows a global understanding of the production of an extended and highly specific macroscopic order by a microscopic organization. It provides a conceptual alternative to the similarly general idea of the genetic specification of extended macroscopic order. I will apply the new conceptual framework in order to make sense of anticipatory behavior, without representational specification.

Before turning to behavior it will be useful to introduce some terminology to accompany the interpretation given here to gene-trait relations. It has been argued that genes do not specify macroscopic order. This order is inherent in the self-organizing system. Nevertheless, when genes act as control parameters, there will be a connection between genes and traits on a large scale. There should be, of course, as there is ample empirical evidence relating specific genes to specific macroscopic traits. Consequently, when a coarse enough focus is maintained, genes can still be said to specify traits (Thelen & Smith, 1994). There are two problems with this loose usage of 'specification'. The first problem is that it is very unclear. Whether or not a gene specifies a trait depends on the scalar focus used and can thus be considered to be both true and false, depending on the scale of observation used. Natural language does not usually keep track of the scale at which a statement applies, and talking about 'specification' does not do much to remedy this. The second problem has to do with the implied directness and directedness of the word 'specify'. It neglects the intervening, self-organizing processes and the mutual influencing which goes in both directions. It highlights only the genetic code and the encoded trait and puts them in an unidirectional relation: the code specifies the trait.

In contrast, when genes are interpreted as ICP's, the very existence of the large-scale relations depends on the always slightly divergent and non-repeatable happenings in between code and trait. Two technical terms will be introduced to stress this point. Genes will be said to be '*appropriate*' or not, referring to their relevance for generating happenings at larger scales. Macroscopic traits are '*sufficient*' or not, depending whether they suffice to fulfil the requirements posed by the microscopic living organization. Both terms relate to the intermediate scale relations and stress the historical, contingent nature of the relations between microscopy and macroscopy. It can be acknowledged that genes are appropriate, while, at the same time, rejecting their interpretation as a specific symbolical code, a description, or a blueprint of macroscopic form (Pattee, 1977, 1987). If genes are a set of stored ICP's, this symbolic interpretation does not apply. Genes do not encode macroscopic form. Rather, they help produce it in conjunction with cytoplasmic and inter-cellular processes.

Genes are importantly related to macroscopic structure because they modulate and are modulated by the living organization which ultimately comes to exhibit a macroscopic structure, or not. Genes are appropriate when their presence is a condition for the occurrence of macroscopic form. But this only applies within the context of the living organization in which they take part. There is no

meaning or symbolism intrinsic to genes outside of this context. Within this context they are only entities with the propensity to help attain macroscopic orderings which are suitable to maintain the living system's integrity. The relation between genes and macroscopic traits derives from the mediating process, and is basically an arbitrary connection.

Sufficiency replaces the other side of the seeming specificity of large-scale gene-trait relations. There is of course a degree of specificity present. For instance, for a leopard it is important for it to have four legs, one tail, one head and so on. The point here, however, is that next to such general specificity there is a lot of room for individual variation. In that sense, the large-scale structure does not have to be a specific one at all. It only has to fulfil certain standards of sufficiency. To return to the leopard, it tends to have spots, but how these are distributed across its pelt varies. Thus, while 'specificity' is conceptually connected to a precise and exact macroscopic structure, 'sufficiency' focusses our attention on the variability and contingency of the macroscopy. The underlying microscopic processes do not have to converge on one specific point, but on anything which falls within a much wider area of acceptable macroscopic structures.

3.4 Can anticipatory behavior be guided by internal control parameters?

Genetic functioning is no longer interpreted in terms of a simple specification model. The latter only applies within a coarse grained analysis of gene-trait relations. It is now time to turn around the analogy in which genes are envisioned as the "brain of a cell", and the image of an 'intelligent and knowledgeable brain' is used as a way to understand gene action. I will use the modern interpretation of genetic activation to make sense of the relation between the nervous system and anticipatory behavior.

The big picture of the morphogenetic conceptual framework consists of a cellular microscopy which succeeds in generating a sufficient order at increasingly large spatio-temporal scales. The following features appear to be crucial for this phenomenon: (a) There is self-organizing, dynamical organization in which circular relations between macroscopic boundary conditions at $S(n)$ and microscopic dynamics at $S(n-1)$ produce macroscopic orderings at $S(n)$. (b) The microscopy contains selected variables which—in specific time windows and under appropriate boundary conditions—can act as internal control parameters. (c) The internal control parameters are part of a regulatory network at $S(n-1)$ which modulates the timing of their activation. (d) Under the influence of the modulated timing of the internal control parameters an epigenetic pathway is traversed which results in an ordering at the larger scale of $S(n+1)$. (e) Success or failure of generating order at $S(n+1)$ must eventually feed back to the regulatory network at $S(n-1)$ (e.g. by selection or learning).

To apply the morphogenetic conceptual framework to behavior, these features will have to be present in the behavioral context. The task at hand is to argue that this is a plausible assumption. This task is both simple and complex. It is simple because these features often almost self-evidently apply to neural and behavioral phenomena. There are many obvious correspondences. What makes it complex is to establish how deep such correspondences run. Offering detailed accounts of the neural, musculo-skeletal and environmental equivalents of these features would be a huge enterprise, one which would occupy the agenda of complete research institutions for extended periods. However, the immediate goal is limited to establishing that the morphogenetic framework is at least consistent with the behavioral facts. So, what I will do is point out the most conspicuous correspondences and hint at some of the details which could actually implement the morphogenetic conceptual framework.

In Section 2, behavior was conceptualized as the mutual coupling between the differently-scaled dynamics of the neural system, the musculo-skeletal system and the environment. This dynamical organization provides an obvious candidate to play the role of feature (a). The initial condition for applying the morphogenetic conceptual framework to behavior is thus fulfilled. In accordance with feature (d), it was also argued in Section 2 that regular, behavioral trajectories emerge at a larger spatio-temporal scale than more basic organism-environment couplings. After all, this correspondence drew out the conceptual link with morphogenesis in the first place. The remaining features are more specific and arguing for their presence is more speculative. Nevertheless, it is clearly possible that the neural system, the musculo-skeletal system and the environment have the required features.

First, it is very probable that the nervous system is capable of providing internal control parameters for behavior (b). Maybe the most convincing argument in favor of this possibility is the sheer complexity of the nervous system. Anything could happen there. Providing ICP's should not be a problem. Several general features point in this direction. The brain shows many mappings in which environmental features map onto specific neural structures. These could play a role in the longer-term guidance of behavior. It is also self-evident that the nervous system operates on multiple time-scales. Humans exhibit fast reflexes as well as slow, reflective actions. Berridge (1990) compared the grooming behavior of several rodent species and found that the large scale structure of grooming was more stable across species than were the component actions. Fentress (1991, 1994) mentions research on rats in which striatal lesions had minimal effects upon movement form but disrupted the integrity of behavioral sequences and made the animals hypersensitive to environmental disturbances. All this points to a dissociation of the neural involvement in behavioral organization at different time-scales. Can these generally supportive properties be interpreted in a way which is coherent with a morphogenetic conceptual framework? Work which is now being done on reinterpreting neural functioning in terms of coupled oscillators is an approach which is congenial to the one advocated here (Alexander & Globus, 1996). A specific argument for the existence of behavioral ICP's comes from Scott Kelso (1995). Kelso's famous 'finger-experiments' demonstrated that simple finger-movements exhibit properties indicative of dynamical self-organization. These self-organizing movement properties are under the influence of non-specific control parameters such as the frequency of the movement. However, when dealing with issues of learning and intentionality, Kelso states: "I argue that it is necessary to incorporate another kind of forcing, namely, that of *specific parametric influences*. ... instead of frequency moving the fingers through different phasing patterns, the fingers are instead required to produce a *specific* phasing pattern." (Kelso, 1995, p.138). Kelso argues that a dynamical self-organizing behavioral process can be guided in specific directions by appropriate control parameters, originating within the brain (ibid., p.140). This fits the bill good enough.³

Another requirement is that behavioral ICP's are part of a regulatory network which modulates the timing of their activation. Well, the nervous system is more or less the prototype for thinking in terms of regulatory networks. While in morphogenesis the network is the abstract part of the system—a set of modulatory influences between different processes—and the produced form the tangible end-result, in the case of the neural system matters are reversed. The nervous system is physically a network. In addition, in case of the human nervous system most of the network is not directly connected to sensory or motor surfaces. Maturana and Varela (1988) mention a ratio of 10:100,000:1 for respectively sensory-, inter-, and motor neurons. A very large part of the nervous system thus seems to have some regulatory function. Bickhard and Terveen (1995, p.310-314) discuss recent work in neuroscience centering around modulatory processes of endogenous oscillatory activity. This research stresses the variation in volume and temporal modulatory relationships which permeates the whole brain. "The larger volume effects are clearly also longer time scale modulations. In the brain, such slower and larger volume modulations can constitute modulations of the already ongoing modulations among neural oscillations and within neural networks" (ibid., p.312). There are clear empirical possibilities for the requisite regulatory network.

Finally, the consequences of large-scale, behavioral order will have to feed back to the regulatory network at the scale of the neural modulations (e). In other words, learning has to take place. This looks relatively simple—learning definitely occurs—but when considering plausible mechanisms which could accomplish appropriate feedback relations, things become remarkably complex. General ideas about how the neural system can change appropriately so that large-scale order arises, have been provided by e.g. Edelman (1987) and Purves (1988). To make successful feedback possible, specific structures at the neural scale are necessary. For instance, learning by reinforcement requires a value system within the neural system to distinguish appropriate and inappropriate actions (Friston et al., 1994). Specific neural pathways which signal positive and negative outcomes of behavior (pain and pleasure) could provide this value. However, for anticipatory behavior, the feedback should apply to large spatio-temporal behavioral structures, not just the last molecular action. Not only the ingestion of food is to be evaluated as good, but also the behavioral sequence which led to having a meal. The

complication here—in comparison with representational specification models—is that ICP's do not form a model which *represents* environmental structure. The appropriate ICP structure cannot be copied from the environment by a perceptual process. As in the case of genes, the environment does not have the power to *instruct* appropriate codings. There has to be a different way to acquire an appropriate ICP structure. How this works is unclear for now, but, there are clearly possible solutions to this problem. To offer just one example, in work on reinforcement learning with artificial agents it is now well established that learning can be greatly improved by predicting future reinforcements and comparing the results with actual reinforcement. This allows the system to take into account a larger time-frame in which its actions are evaluated and changes in ICP's could be realized (Sutton, 1991).

There do not seem to be any intrinsic obstructions to applying the morphogenetic conceptual framework to behavior. The latter can be explained as a dynamical organization which expands its self-organized order over increasingly large spatio-temporal scales by incorporating regulatory networks which modulate and are modulated by 'stored' internal control parameters.

However, all this attention for the possible implementation of this interpretation entails the risk of neglecting the general picture. Superficially it might even seem that there are only slight changes with respect to the AT story. Neural ICP's could be interpreted as representations. As they are also taken to be a highly relevant factor for accomplishing anticipatory behavior, the outward similarity with AT's view on behavior could lull one into thinking that there are no fundamental differences. This is a mistake. Anticipatory behavior is no longer interpreted as the execution of preconceived plans. The ICP's do not constitute a 'program' in any conventional, computer sense. The similarity exists at one specific, large-scale organizational level. The scale oriented, dynamical view stresses that the interactions between dynamical processes happening at multiple spatio-temporal scales are essential for building up and maintaining this large-scale coordination on which the very idea of representational specification is based. In Section 4, I will discuss whether ICP's are 'a form of representation'. First, I will be more specific about what it *means* to say that anticipatory behavior consists of a structure extending over multiple, increasingly large, spatio-temporal scales.

3.5 Anticipatory behavior as a self-organized regular trajectory.

When the morphogenetic framework is used to interpret behavioral phenomena, anticipatory behavior turns out to be a developmental process. This is a claim about behavior itself. It does not mean that behavior is the result of developmental processes, which produce a nervous system capable of instigating anticipatory behavior. The claim is that every action itself is *literally* a developmental process, played out on a comparatively short time scale—usually ranging from tens of milliseconds to seconds and minutes, but sometimes extending over hours, days or even longer. Anticipatory behavior is a macroscopic spatio-temporal form which is each time self-assembled anew from dynamical, self-organizing interactions between multiple scales of organizations. Thelen and Smith say the following in this respect: "Each act is a new behavioral form: stable and predictable in some of its features, but variable, flexible, and adaptive in each instantiation." (1994, p.73). A behavioral process, from its beginning to its end, traverses an epigenetic pathway, that is, it proceeds in a historical and contingent fashion (*ibid.*, p.142). Following Yates (1993), I will call such a self-organized trajectory a "regular trajectory".

Yates contrasts the concept of a regular trajectory with 'Newtonian trajectories' (see Section 2.2). A Newtonian trajectory is characterized by a precisely defined change in a set of variables which describe a system of interest. This trajectory is, in principle, endlessly repeatable by returning the system to the same initial state and applying the same set of changes. Industrial robots provide a good example of this 'Newtonian' approach. These robots perform relatively complex tasks by being very precisely instructed at a microscopic scale. The instructions sent to the motors set the total macroscopic system in motion. Because of the robot's rigid make up—the motors initiate very precise changes in the joints and the arms are made of stiff materials and securely fastened to a firm support—these microscopic signals translate reliably in macroscopic movements of the robot. In this way, the *specific* and endlessly repeatable macroscopic movements are generated which are so useful in the factory.

There are two kinds of problems with this approach. Firstly, many, very precise instructions are needed to generate the specific macroscopic effects. All the large-scale order has to be present in the initial description, which must rigidly control subsequent happenings. It is a bit like building a house by gluing together grains of sand, instead of using large pre-fab elements in which a lot of the intermediate structure is present in the building material itself. It is difficult to maintain the necessary control when the number of elements becomes large. The other problem is related to the first one. How can disturbances of the linear translation of microscopic instructions into macroscopic movement be dealt with? The large-scale dynamics of a robot's structure tends to interfere with the translation of the microscopic instructions into exact large-scale movements. A robot's arm might be flabby, in which case the instruction to put the joints in a particular position will not lead to the end of the arm being at the required place, at least temporally. If the robot is made more massive to prevent these disturbances, it will more readily show slippage. After performing the same movement many times the robot will wrench itself loose from its support. Such disturbances will result in a scattering around the intended movement result, a scattering which will have to be counteracted by keeping the robot and its environment as tightly constrained as possible. For these robots to work, a highly restricted and stereotypical environment is necessary, together with endless calibration of the machine by human engineers to keep it that way. It is not an attractive setup for dealing with real world environments in which disturbances of 'normal' functioning are the rule rather than the exception.

In contrast, a self-organized, regular trajectory takes the existence of order at multiple scales as its starting-point. A regular trajectory, spanning several scales of organization, emerges when the dynamics at multiple scales become coupled to one another. The neural system modulates short term organism-environment interactions. These short-term interactions in turn modulate happenings in the environment on a longer time-scale, and so on. Large-scale order results from intrinsic self-organizing tendencies at that scale. This order is manipulated by changing control parameters within the microscopy. It is not specified beforehand within the microscopy. The make-up of the intervening levels of organization ensures a *sufficient* result (Section 3.3), not the specificity of the precisely instructed and tightly constrained Newtonian trajectory. The microscopy 'uses' the intrinsic order at larger scales to generate the trajectory. This order (or the disturbances for a Newtonian trajectory) need or, even stronger, should not be suppressed or minimized. What is needed at smaller scales is a regulatory network which plays these self-ordering tendencies. When this works appropriately, regular trajectories take form. In contrast to the Newtonian ones, they are never exactly the same, never exactly repeatable. Each one is a historical, contingent event.

A way to visualize this is by thinking of circles in circles (Fentress, 1991). The dynamics belonging to a particular scale $S(n)$ can be represented by a circle. This circle is in turn surrounded by a larger circle representing the dynamics of $S(n+1)$, and so on (see Figure 3). The arrows represent the reciprocal relations between different scales. The total picture gives the image of an expanding, reciprocal influence of an initially small organization which subsequently manages to draw increasingly large-scaled dynamics into its influence. At the same time this picture can still accommodate the traditional image of representational specification, which turns up as a coarse view on the nested set of dynamical structures. When all the details of the mediating processes are kept out of view, a seemingly direct link between factors at the neural scale and macroscopic events will be seen.

=== insert Figure 3 about here ===

Despite their rough, outward resemblance, a Newtonian and a regular trajectory are very different. The first is a precisely defined change in a set of variables over time. The second consists of a change in a set of variables at $S(n-1)$ which act as control parameters that modulate and change the dynamics of a set of variables at $S(n)$, which in turn do the same for the dynamics at a scale $S(n+1)$, and so on. Several sets of descriptions are needed simultaneously to keep track of this multi-level organization. Making this difference between Newtonian and regular trajectories implies, for example, that large-scale movements, as performed by industrial robots on the one hand, and humans and animals

on the other, reflect different organizational principles. Behavioral research should be sensitive to these different organizing principles behind outwardly similar behavioral phenomena.

Interpreting anticipatory behavior as a regular trajectory has implications for the relation between the neural factors—which might act as ICP's—and achieved goals. In a model based on representational specifications the relation between a relevant neural factor and a related external macroscopic state is seen as fairly direct. Both are seen as being specific to one another. The relation between ICP's and macroscopic structure is better characterized in terms of appropriateness and sufficiency. This relation is much less direct, does not draw on an abstract isomorphism or representation and stresses the importance of the self-organizing processes which are needed to generate large-scale order. Talking about a *specific* goal to be achieved generates the impression of a tightly constrained end-result. Using the concept of *sufficiency* changes this picture. The trajectory, as well as the goal itself, are now much less pinned down. In the Newtonian case, an obvious strategy would be to define the goal-state and back-track from there until a route to the goal is found. On the other hand, in the case of real behavior it is normally not necessary at all to reach a very specific goal. A variety of states will do, as long as they fall within a certain range. Going out for pizza does not imply that there is only one 'good' outcome for this behavior, namely eating the piece of pizza which you actually ate. Innumerable slices of pizza of sufficient quality and served within a reasonable time-frame, would have been equally acceptable. There is only specificity after the fact: Only afterwards is it a historical truth that a particular piece was eaten.

Again, a comparison with current industrial robots is enlightening. Robots are built to perform tasks for human users. These users do have very specific goals in mind for their expensive robots. These tasks are often thought to be relatively simple, such as house-cleaning or making a tuna-sandwich. Given the analysis of behavior presented here, performing such specific tasks at a specific time would be at the upper end of behavioral complexity. These are not simple tasks at all. Behavior is rather a general manipulation of large-scale dynamics in ways which over many trials tends to be successful often enough to enhance the continuing existence of living organizations. All animals would have extreme difficulties with the tasks envisioned by the average roboticist. As a way of modelling behavior, roboticists seem to be held hostage to the commercial demands for useful robots without a sufficiently clear appreciation of the real problems surrounding adaptive and anticipatory behavior.

In summary, anticipatory behavior occurs when an embodied and situated neural system is capable of generating regular trajectories, which lead to a sufficient macroscopic order. Given a capacity for self-organized behavioral regularities at a short time-scale, a regulatory network which modulates a set of control parameters will be able to guide this process over longer time-scales in a way that makes it relatively independent of the immediate environment. It will enable the system to achieve long-term goals. An extended interactionist account of adaptive behavior can thus deal with problems which formerly necessitated representational specifications.

4. Should behavior-related ICP's be interpreted as representations?

This paper started out referring to a discussion between representationalists and interactionists: those who do and do not think that representational specifications—representations acting as an internal model to guide behavior—are necessary to explain the generation of behavior. There is a tendency in this discussion to think that the radical interactionists are making a fuss about words. One often hears exclamations like: "Of course Brooks' insect-robots incorporate representations. He just doesn't want to call them representations." These people take the existence of representations in behavioral systems as a definite fact. However, those interactionists who oppose the necessity for internal representational models do take the anti-representational case more serious than that (Keijzer & Bem, 1996). The interactionist claim is that representations are specific theoretical entities, that one should do without when trying to understand adaptive behavior. How does the morphogenetic conceptual framework bear on this discussion?

The account presented started out with an interpretation of organism-environment interaction in terms of scale-relations and self-organization. The concept of representation does not do any work here.

However, to accommodate the more representation-hungry problem anticipatory behavior a morphogenetic conceptual framework was introduced. This framework involves the notion of internal control parameters and it might look plausible to interpret these ICP's as some form of representation. Several properties of ICP's point in this direction. (1) Like the genetic code, behavior-related ICP's are definite theoretical entities which stand out from the short-term operation of the nervous system. (2) They also function to guide long-term behavior, just as representations do in specification accounts. (3) In the case of morphogenesis the genetic factor was also interpreted as a set of instructions which already embodied the macroscopic form. As this resulted in a very successful research-program, why not maintain a representational interpretation for behavior-related ICP's?

Are the radical interactionists then proved to be in the wrong, given the morphogenetic conceptual framework and the need to deal with anticipatory behavior? Well, there are also good arguments against interpreting ICP's as representations. Firstly, there are many conceptual differences between the concept of 'representation' and ICP's: A representational interpretation is limited to one particular perspective on a multiply scaled organization. Behavioral ICP's are explicitly defined within the context of multiple scales of organization. To deem the two equivalent is putting too much value on one particular perspective on behavior. Representation is, literally, a *coarse* view. In contrast to representations ICP's are intrinsically connected to a regulatory network of which they are a part. Also, ICP's do not re-present external circumstances in an abstract way. Such an interpretation goes right against the grain of the idea of a regular trajectory. The macroscopic order is newly generated, it is not already encoded within the organism's ICP's.

Secondly, a representational interpretation could easily interfere with the morphogenetic conceptual framework. Equating ICP's with representations amounts to the injection of a particular set of thought habits into a tentative and still fragile, interactionist account of behavior. Representations are firmly associated with higher level concepts such as intentionality and the mental frame of reference in general. Interpreting ICP's as representations brings in a lot of conceptual ballast. Without it there is much more freedom to develop new ideas and explanations, as is now being done in embryology (see e.g. Nijhout, 1990). It would wrestle behavioral explanation free from the old Cartesian picture of a separate mind situated in the head and directing behavior. It would be a step in the direction of a much more natural treatment of behavioral phenomena.⁴

Finally, the sheer *possibility* of a representational interpretation should not be taken as a compelling reason to actually interpret ICP's as representations. Being able to establish a reliable relation between an environmental state and an ICP, or some neural state in general, does not imply that the latter is necessarily a symbol. Noticing that a tree rises from the ground up to a noticeable height does not make it a tower. Trees and towers are different things, even though they share certain properties. The representationalists seem to claim that everything within the nervous system which covaries with external factors has to be a representation. The counterargument is simple. Why couldn't we be more discriminative than that?

Given these arguments pro and con, does the morphogenetic conceptual framework feature representations or not? My own judgement would be a denial. The concept of 'ICP' is definitely not the same as that of 'representation'. It would be a sensible policy to signal this change by a change of vocabulary. But then, like the defenders of the representational view are wont to say: why make a fuss about words? It is the concepts behind the label that matter. I would thus be happy to oblige anyone who wants to uphold that ICP's are 'some form of representation'. The real issues lie after all with the ideas behind the label.

The presented conceptual framework, with its ideas imported from embryology, expands the interactionist account of behavior in a way which enables it to explain the occurrence of anticipatory behavior—at least, in theory. The thing being offered so far is, of course, only an idea, an alternative, very general, conceptual structure for thinking about the organizing principles behind adaptive and anticipatory behavior. Its validity will depend on its usefulness as a source for more concrete ideas concerning the origins of behavior. Empirical research and the development of more elaborate and concrete models of behavior will have to decide on that. Still, the intrinsically good thing about this framework, come what may, is that it focusses attention where it should be: onto the mediating

processes which actually generate behavior. Morphogenesis is a phenomenon where a lot of solid facts concerning its biochemical, genetic, cellular and topological organization eventually led to a more general understanding of this process. The promise is that it offers a theoretical lead to direct our attention to those facts which are central to the organization of behavior.

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Notes.

- 1 Both the interactionist and the regular cognitive explanation are to be opposed to behaviorism. Behaviorism is concerned with regular ways to shape existing behavior into forms which have specific (e.g. adaptive and anticipatory) characteristics. The discussion here focusses on the organization required to generate any adaptive, anticipatory behavior at all. Not on how it is changed by learning.
- 2 Both Goodwin and Kauffman are proponents of a so-called 'developmental tradition' in biology (Resnik, 1994; Griffiths, 1996). The account sketched here is in agreement with this tradition. Sometimes the developmental tradition is held to be in opposition to the classical neo-darwinian position (Dennett, 1995). The developmentalists argue that not all order which is present in living nature is the result of selection. For example, Kauffman remarks that lipid membranes, which provide such useful cell boundaries, do not originate in genetic instructions. Lipid membranes are a physical phenomenon and they come for free under the proper circumstances (Kauffman, 1993). However, acknowledging the importance of self-ordering principles in living nature does not in any way detract from the importance of selection as a crucial factor in generating order (ibid.). I would like to follow Depew and Weber's (1995) lead and hold that the dynamical view could form a refinement and extension of darwinian ideas, similarly to how mendelian genetics and the statistical approach to population genetics formed the 'modern synthesis' of neo-darwinism. There is no reason to posit any deep disagreement with basic darwinian insights.
- 3 Notice that Kelso gives an intentional interpretation to these parametric influences and uses the word 'specific' in this context. For Kelso this is a way to combine self-organizing systems with intentionality. However, it is strange to interpret intentionality as a factor coming from outside the system under description, and imposing its intended order on that system as some mysterious force. To me it makes more sense to interpret ICP's as non-intentional, non-specific (but appropriate) control parameters, and to think of intentionality as a higher-level property that applies to an intelligent system as a whole (Keijzer, 1997; see also note 4).
- 4 The last suggestion might raise a very fundamental worry with this approach: Is it not a way towards a full reduction of the mind, and the loss of everything which makes us special as sentient and rational beings set apart from a merely mechanical and material world? This worry has certainly been a prime motivation for maintaining representations within behavioral explanation (Fodor, 1981; 1987; Dretske, 1988). Given a multiply scaled perspective on the world, the fear seems to be for a catastrophe which is not coming anyway. There are many levels or scales of organization. Nature is more than 'just' physical processes. It involves chemical-, geological-, biological-, psychological and sociological processes as well, to name a few. Behavior and the mind seem to be firmly entrenched phenomena within the scalar hierarchy. Both are readily interpreted as higher levels of organization, the occurrence of which should be explainable by lower-level processes. Making mental concepts part of a lower-level explanation of anticipatory behavior does not make the mind more real than it would be on its own accord. It only threatens to make behavioral explanation less tractable.

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